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THE GENESIS OF THE CRYSTALLINE IRON-ORES.

BY ALEXIS A. JULIEN.

In an age which admits its special indebtedness for material advancement to the industries connected with the manufacture of iron, and in a country in which these industries have been so vastly developed as in this, the question of the origin of that metal has long possessed, and must always retain, a high degree of interest. So far as relates to the limonites, turgites and bog-ores, the question has met with a satisfactory answer in the theory of the concentration of these ores by the percolation of organic acids, as fully presented in the writings of Bischoff, Hunt and others; especially as the process can be actually observed and studied in progress in the lakes, marshes and bogs of the present day. But the mode of genesis of the crystalline ores—hematites, magnetites, menaccanites, and their mixtures—enveloped partly in the sedimentary strata and chiefly in the still more ancient crystalline rocks of archæan age, can be only inferred from analogies. Nor can the problem be considered as solved by any or all of the numerous theories which have so far been advanced. These theories may be naturally divided into two classes, as they may refer the iron-ores, enclosed in the subterranean strata, to an extraneous or to an indigenous origin.

A. THEORIES OF EXTRANEOUS ORIGIN.

To begin with the former, we have

1. *Meteoritic fall.* This startling theory has been suggested to account for the enormous mass of martitic specular iron-ore, claimed to be the most extensive known single deposit of iron-ore on the continent, that of the Cerro de Mercado, two miles from Durango, Mexico. "Cerro de Mercado is a mountain, one mile long, one-third of a mile wide, and from 400 to 600 feet in height. The ore-surface of the mountain aggregates over 10,000,000 square feet; but there are indications that the ore is not all above ground, and the engineer's report declares it to be an enormous aërolite, half imbedded in the level plain on which it lies." Such a view is sufficiently controverted by the mineralogical constitution of

the mass, and its structure—"immense veins of specular iron-ore standing nearly vertical."¹

2. *Eruption as dykes.* According to this genetic view, the crystalline iron-ores have been extruded from the interior in a pasty condition, like a lava, through fissures in the superficial strata.² This theory has been recently further developed in reference to the banded jaspery iron-ores of Michigan, and it has been advanced that the banding and lamination of these ores are similar in character and origin to those strongly marked in rhyolites, furnace slags, etc.³ The mineralogical constitution and infusibility of these ores, their distinctly sedimentary lamination, etc.,⁴ clearly testify to the unsoundness of these hypotheses.

3. *Sublimation into fissures.* The inconsiderable crusts of specular oxide, which have been observed in the vicinity of volcanoes, such as Vesuvius, have certainly no relation to the enormous *bedded* masses, distributed throughout the world, at a distance from volcanic centres.

B. THEORIES OF INDIGENOUS ORIGIN.

The theories of this class differ in ascribing the origin of iron-ores to either chemical or mechanical agencies. Nine chemical theories have been proposed.

4. *Concentration from ferriferous rocks or lean ores,* by the solution and removal of the predominant constituent, *e. g.*, silica, by means of thermal solutions. Indeed it has been shown⁵ that a concentration, in a similar way, of the ferriferous constituent, in the lower carboniferous limestone and dolomites of the Mississippi basin, through the removal of the more soluble calcium carbonate by carbonated waters, has apparently produced extensive deposits of limonite, *in loco originali*. But there is no evidence

¹ B. Silliman, *Am. Jour. Sci.*, 1882 (iii), xxiv, 375; and J. Birkinbine, *Chicago Min. Jour.*, 1882, ii, No. 4, p. 184.

² J. D. Whitney, *The Metallic Wealth of the U. S.*, p. 433.

³ M. E. Wadsworth, *Proc. Bost. Soc. Nat. Hist.*, 1880, xx, 470; and *Am. Jour. Sci.*, 1881 (iii), xxii, 403.

⁴ J. D. Dana, *Am. Jour. Sci.*, 1881 (iii), xxii, 320, 402; J. S. Newberry, *Sch. of Mines Quarterly*, Nov., 1880.

⁵ J. P. Lesley, *Report on Brown Hematite Deposits of Nittany Valley, Pa.*; R. Pumpelly, *Geol. Surv. Mo., Prelim. Rep. on Iron-ores*, 1872, 8, *et seq.*

of the relation of any of the crystalline iron-ores, enclosed in sediments of plainly submarine origin, with any such subaërial process. Even were the theory satisfactory in regard to the pure ores, the essential question remains unanswered, viz., the genesis of the original "ferriferous rocks or lean ores" themselves.

5. *Saturation of porous strata, e. g., of sandstone*, by infiltrating solutions carrying iron oxide.¹ This theory, however applicable to certain rock-masses rich in hydrated ferric oxides, can account neither for the concentration of the huge and pure bodies of the true ores, nor for the alternation of siliceous and ferriferous laminæ and layers in the lean ores.

6. *Infiltration into subterranean chambers and channels*, depositing pipe-ores and limonites in widened crevices and joints of the more recent limestones or other sedimentary rocks, or in cavities overlying impervious strata.² The lenticular form, laminated structure, intercalation of the material of the matrix, enclosure of the ore-bodies in the bedding-planes, and other facts, markedly distinguish the crystalline ores from the limonites formed by such a process.

7. *Decomposition of pyrite*, and other ferruginous minerals, enclosed in decaying schists, and transfer of the iron-oxide in solution as ferrous sulphate.³ The precipitation of the iron-oxide has been sometimes attributed to simple oxidation, more usually to the production of ferrous carbonate, by reaction between the ferrous sulphate and the calcium carbonate of the limestone, afterwards converted into limonite by oxidation and hydration.⁴ This theory has had only local application, even to the limonites, and its connection with the crystalline ores is rendered improbable by the absence of associated limestones, or, if present, of evidences of their erosion, etc.

8. *Derivation from original deep-sea deposits* of hydrous ferric oxide, or of ferrous carbonate, dehydrated by subsequent heat, and deoxidized by hydrogen.⁵ By a modification of this theory, the jasper-ores have been connected with the ferruginous and mangan-

¹ Emmons, Nat. Hist. N. Y., iv, 94.

² F. Prime, Jr., Am. Jour. Sci., 1875 (iii), ix, 433.

³ T. S. Hunt, Nat. Ac. Sci., Nov., 1874.

⁴ G. Bischoff, Chem. and Phys. Geol., i, 236; F. Prime, Jr., *loc. cit.*; W. B. Rogers, Geol. Penn., 1868, ii, Pt. ii, 722, 729.

⁵ J. P. Lesley, The Iron Master's Guide, p. 374.

iferous nodules which have been dredged from the surface-layer of the deep-sea ooze of our present ocean-bottoms.¹ All the evidence so far gathered, however, shows no correspondence between the phenomena, the ferriferous contents of the ooze consisting of irregular crusts and nodules, never continuous nor interlaminated with silica. On the other hand, there is abundant evidence that the strata associated with the crystalline iron-ores are mostly shallow-water or shore-deposits, in large part conglomeritic.

9. *Deposit from springs*, by oxidation and precipitation from solutions of ferrous carbonate, on exposure to the air at their issue.² Such deposits, it is admitted, are local and limited, and the theory can have no bearing on the ordinary wide-spread crystalline ores.

10. *Alteration of diffused ferric oxide*, disseminated through sediments, into ferrous carbonate, in presence of vegetable matter, and its accumulation in particular layers by processes of filtration and segregation.³ The vague processes thus invoked to account for the accumulation of ores are not accepted as satisfactory, even for the carbonates of the coal measures, lying in definite planes. Nor do the sheets and beds of crystalline ores usually show the irregular characteristics which may be attributed to processes of segregation.

11. *Metamorphism of ancient bog-ores*. The reference of the crystalline iron-ores to this origin has been thus stated by Dr. Hunt: "I see no reason for assigning any other than a sedimentary origin to the magnetic and specular iron-ores of the crystalline schists; nor do I conceive that the conditions under which they were deposited differed essentially from those which at the present day give rise to beds of limonite and ochre."⁴ Again he observes: "The organic matters reduce the peroxide of iron to a soluble protoxide, and remove it from the soil, to be afterwards deposited in the forms of iron-ochre and iron-ores, which by subsequent alteration become hard, crystalline, and insoluble."⁵

¹ W. O. Crosby, Proc. Bost. Soc. Nat. Hist., 1879, xx, 168.

² G. Bischoff, Chem. and Phys. Geol., i, 155-157, 166-167.

³ W. B. Rogers, Geol. Penn., 1868, ii, Pt. ii, 737.

⁴ Letter of Dr. T. S. Hunt, 1858, quoted in Lesley's Iron Master's Guide, p. 365. See also Vanuxem, Nat. Hist. N. Y., Geol., 3d District, p. 267.

⁵ T. S. Hunt, Chem. and Geol. Essays, 22.

Le Conte also states: "Therefore we conclude that both *now* and *always* iron-ore is, and has been, accumulated by organic agency."¹

Prof. J. D. Dana remarks,² concerning the Upper Silurian deposits: "The beds of argillaceous iron-ore * * * could not have been formed in an open sea, for clayey iron deposits do not accumulate under such circumstances. They are proof of extensive marshes, and, therefore, of land near the sea-level. The fragments of crinoids and shells found in these beds are evidence that they were, in part at least, salt-water marshes, and that the tides sometimes reached them." In reference to the Laurentian deposits, he states: "Limestone strata occurred among the alternations, and argillaceous iron-ores, though vastly more extensive. * * * The argillaceous iron-ore has become the bright hematite or magnetite, and it is banded by, or alternates with, schist and quartz, etc., which were once accompanying clay- and sand-layers."

Dr. Kitchell long ago opposed the theory of the igneous or eruptive origin of the magnetic iron-ores of New Jersey, maintaining that they "were of sedimentary origin, and had been deposited just as the gneiss and crystalline limestone had."³ With this view Prof. Cook coincides, in the following statement: "The magnetic iron-ores of this State have originated from chemical or mechanical deposits, just as our hematites and bog iron-ores do now."⁴

In opposition to this theory, in its reference to subaërial bogs or marshes, it must be considered that the enclosing and associated strata bear universal testimony, both in their contents and the form of their superficies, to their submarine mode of deposit. On the other hand, if the bog-ore theory were applicable to these ores, every ore-bed would imply a terrestrial plane for the reception of the subaërial bog deposit, *i. e.*, for every ore-lens a corresponding elevation above the sea-level and ensuing subsidence of the entire underlying stratum. On the contrary, no evidence has been shown in the archæan strata of any subaërial surface; all appear to be submarine sediments, and that still more ancient rocky terrane which formed the coast whose débris, poor in iron,

¹ J. Le Conte, *Elements of Geology*, 375.

² J. D. Dana, *Manual of Geol.*, p. 231 and 155.

³ W. Kitchell, *Geol. Surv. N. J.*, 2d Rep., 1855, 155, 229, etc.; and 3d Rep., 1856.

⁴ G. H. Cook, *Geol. of N. J.*, 1868, 61.

was deposited or strewn over the ancient Laurentian sea, and upon whose surface bog-deposits may have rested, seems to have been entirely buried up beneath later sediments. Again, the strongly marked lenticular form and laminated structure of all deposits of crystalline iron-ores—and even of the numerous smaller lenses, parallel or overlapping, which make up the large deposits—are unmistakably characteristic of marine accumulation, Neptune's own royal stamp. A bog-ore deposit is almost always irregular in outline, concretionary and cavernous in structure, and commonly characterized by concentration in pockets and groups of isolated lumps. One can rarely fancy any traces of such peculiarities in the compact symmetrical lenses which make up ordinary deposits of magnetite.

The complete dehydration and partial deoxidation of the hydrated iron-oxide of a bog-ore, necessary for its conversion into a magnetite, must have produced an enormous contraction; but of this there is rarely any evidence, such as might be expected, in the disturbance of the lamination of the ore, and of the stratification of the surrounding rock.

It is of common occurrence that a bed of crystalline iron-ore overlies a bed of limestone, in immediate contact (*e. g.*, at the Baldwin-Forsyth mine, Hull, Canada); and yet the surface of the latter is perfectly plane, presenting no trace of the pitting and erosion¹ to which so soluble a material would have been subjected by the action of the organic acids supposed to have been concerned in the concentration of the ore in a bog.

Although graphite does often occur in intermixture with the crystalline ores, its general absence seems to prove that it cannot be chiefly derived from the organic matter (1 to 36 per cent.) contained in all limonites, but rather, it may be, from the algæ and marine plants sometimes finding their growth and entombment in the sands, even of iron-oxide, in shallow water. To the deoxidation produced in the decomposition of the remains of such plants, the content of sulphur in many iron-ores may be due.

12. *The metamorphism of ancient lake-deposits* of limonite passing into hematite, corresponding to the oolitic "fossil ore" of the Clinton group of the Upper Silurian, to the "mustard seed" ore described by Sjörmalm, which is deposited near the banks of

¹ B. Von Cotta, *Ore Deposits*, 249, 284.

the present Swedish lakes,¹ etc. This "Lake ore" theory² seems to be valid for a large number of huge deposits of the crystalline ores, and also satisfactorily accounts for the abundant presence of apatite in many ore-beds. It may be fittingly applied, therefore, in explanation of the phenomena seen in those deposits which contain a notable amount of calcium phosphate; most of those which consist of hematite, or of magnetite passing into or occasionally enclosing hematite, viz., in this country those of Cerro de Mercado, of Southern Utah, of Port Henry, N. Y., etc.; and the beds of magnetite which present the botryoidal and concretionary aspect and radiated structure of limonite, *e. g.*, in Southern Utah.³

On the other hand, the poverty or almost entire absence of phosphorus and sulphur in certain ore-beds, and the extreme abundance of titanitic acid, free alumina, garnet, olivine, etc., in others, demand some other explanation.

Two mechanical theories are yet to be considered.

13. *Violent abrasion and transport.* This theory may be best stated in the words of its author:

"That the azoic period was one of long-continued and violent action cannot be doubted, and while the deposition of the stratified beds was going on, volcanic agencies, combined with powerful currents, may have abraded and swept away portions of the erupted, ferriferous masses, re-arranging their particles and depositing them again in the depressions of the strata."⁴

This theory of Whitney was supplementary to his main theory of volcanic eruption of the ferriferous masses, rich in native iron. But to this Lesley properly objects that such secondary deposits would be conglomeritic and also contain metallic iron.

14. *Concentration and metamorphism of iron-sands.* The work of the ocean as a grand abrading agent, and in the transport of the abraded detritus, has been largely studied and described by many authors; but less attention has been paid to the action which goes on, during the shorter or longer period of transport

¹ B. Von Cotta, *Ore Deposits*, 461; *The Geologist*, 1863, 36.

² Dr. J. S. Newberry, "The Genesis of Our Iron Ores," *Sch. of Mines Quarterly*, Nov., 1880, and "On the Genesis of Crystalline Iron-Ores," *Trans. N. Y. Acad. Sci.*, vol. ii, Oct. 23, 1882.

³ J. S. Newberry, *loc. cit.*, 12.

⁴ J. D. Whitney, *Met. Wealth of the U. S.*, 434.

of the detritus, in sorting out the various constituents in reference to specific gravity. Almost every sheltered bay and cove afford instances, not only of local deposits peculiar as to size, *e. g.*, gravels, sands, or fine silt, but concentrated gatherings of the grains of certain minerals, whose separation has been due to the relation of their specific gravity and form to the force of the surf or of local currents. The tertiary sands which border our Atlantic coast present everywhere examples of this continuous and delicate jiggling action of the ocean, in the gathering together—now of black iron-sands, either magnetic or titaniferous, now of red garnet-sands, often of the two intermingled, and, still more abundantly, deposits of pure white quartz-sand. The iron-sands become very prominent in certain localities, *e. g.*, in this country at Killingsworth, on the Connecticut shore of Long Island Sound, on the north shore of the lower St. Lawrence, on the coasts of California and the shores of Lake Huron and Lake Erie, Oregon, etc., and abroad, along the coast of Great Britain, the shores of the Baltic and Mediterranean, New Zealand, Madagascar, and Hindostan. Special attention has been given to the deposits of the lower St. Lawrence, which lie about three metres above high-water mark, and comprise layers of black iron-sand, often nearly pure, from 1.5 to 15 centimetres in thickness.

“An inspection of the iron-sands, from the various localities above mentioned, shows that they all contain, besides the ores of iron, a small proportion of red garnet, and more or less of fine siliceous sand. The latter of the two substances it is possible to remove almost entirely by careful washing of the crude ore.”¹

The frequent purity of these sands may be inferred from the following determinations by Dr. Hunt of their content of *quartz and siliceous residue*:

Rivière du Loup (in Chaudière Valley),	4.80 per cent.
Moisie, ²	5.92 “
Quogue. Long Isd., N. Y. (quartz and red garnet),	17.00 “

In other parts of the world, especially where volcanic or crystalline rocks compose the coast-line, other minerals, such as olivine

¹ Dr. T. S. Hunt, Rep. Prog. Geol. Can., 1866-69, 261-269; also, Canad. Nat., 1872, vi, 79.

² The washed iron-sand contains 0.70 per cent. of sulphur, and 0.007 per cent. of phosphorus.

(in the Sandwich Islands), hornblende, augite, volcanic glass, etc. (on the Mediterranean), often constitute the sands along the shores. Beach-sands, where non-calcareous, consist chiefly of the following minerals,¹ which are arranged in the order of their specific gravities:

	S. G.
<i>Quartz</i> (and chert),	2·5—2·8
<i>Olivine</i> ,	3·3—3·5
<i>Garnet</i> ,	3·1—4·3
<i>Chromite</i> ,	4·3—4·6
<i>Menaccanite</i> ,	4·5—5·
<i>Magnetite</i> ,	5· —5·1

It is a significant fact that in the metamorphic, crystalline rocks of our continent, from Canada to Alabama, we find the same minerals concentrated also in rock-form, viz.:

Quartzite (siliceous schist, jasper, etc.): common everywhere.

Chrysolite (or dunite. Largely converted into serpentine, etc.): Canada, Michigan, North Carolina, Georgia, Alabama, etc.

Garnetite (or garnet-rock. Sometimes made up of manganese-garnet): Canada, New York, North Carolina, etc.; in close association with magnetite at Franklin and near Andover, N. J., in Grenville, Canada, etc. Doubtless in some cases the origin of this mineral (as well as of olivine), especially if crystallized, must be assigned to indigenous development in the course of metamorphism. But, at the Buckhorn Mine, Harnett County, N. C., my own examination of the section, 61 metres in height, confirms the statement of Prof. Kerr,² who notes the following series (from above downward):

Specular ore (11 metres).

Manganesian ore.

Slaty manganese-garnet.

Feldspathic gneiss.

Manganese-garnet.

Gneiss.

¹ In regard to pyrite, its ready decomposition has usually prevented its concentration in sands. As to hematite, its foliated texture seems to have resulted both in its wide transport and distribution, resisting concentration, and in its after conversion into hydrated peroxide.

² Geol. N. C., 1875, i, 222.

Here the garnet certainly occurs in ancient sedimentary layers, whose partial decomposition has saturated the ore with manganese oxide; while the small admixture of magnetite, frequently dispersed through the hematite, points to the original sediment of iron-sand.

Chromite: Massachusetts, Pennsylvania, North Carolina, etc.

Menaccanite: Canada, New York, New Jersey, Pennsylvania, etc.

Magnetite: common everywhere.

Compound varieties also occur in abundance, which correspond closely to the mixtures of the same minerals in the sands along the coast, viz.:

Magnetic quartzite (martitic and hematitic jasper-schists, etc.): common everywhere.

Magnetitic garnetite (also hematitic and *manganesian*): Buckhorn Mine, N. C.

Chromitic dunite: Canada, North Carolina, Alabama, etc.

Chrysolitic menaccanite (with magnetite): Cumberland, R. I.¹

Chrysolitic magnetite: O'Neil Mine, Monroe, Orange County, N. Y.²

Garnetiferous magnetite: mines in Saratoga and Washington Counties, N. Y., etc.

Similar allied rocks occur abundantly in foreign countries: dunite and chrysolitic rocks in Europe, New Zealand, etc.; chrysolitic magnetite, at Taberg, Sweden;³ magnetite and menaccanite, in many localities.

Garnet, together with hornblende, augite, cassiterite, apatite, etc., has been observed in admixture with the magnetites of many foreign deposits, *e. g.*, of the Thorbjörnsbo mine at Arendal, Sweden; of Traversella, in Piedmont; of Berggieshübel, in Saxony; of Schmiedeberg, in Silesia, etc. F. Wöhler relates:

"We spent a day in the large iron-mines of Langbaushytta. The gangue of the fine magnetic iron-ore is frequently brown

¹ M. E. Wadsworth, Bull. Mus. Comp. Zool., 1881, vii, 183.

² J. D. Dana, Am. Jour. Sci., 1881 (iii), xxii, 152.

³ A. Sjören, Neues Jahrb. für Min., 1876, 434.

garnet, which is found in large quantities at the mouth of the mine, and often serves as flux for the reduction of the ore."¹

As the rock-strata, associated with all these varieties, are undoubtedly of marine origin, and indicate deposition in shallow water, it is natural to infer their correspondence in origin, in many cases, with the unconsolidated shore-deposits of the present day. In a recent search through the scientific literature of the subject for any similar view, the following statement was found concerning the crystalline iron-ores of Canada, in which this theory has been, with some reserve, associated with the bog-ore theory :

"It seems possible that, in some cases, beds may have been formed by the accumulation of iron-sands, just as they are forming in the Gulf of St. Lawrence to-day, the material being derived from the disintegration of pre-existing crystalline rocks. Such beds we should expect to contain, not only magnetite, but ilmenite, and it is well known that in many cases, ores, on being pulverized, may be more or less completely separated into a magnetic portion, containing little or no titanio acid, and a non-magnetic portion consisting essentially of ilmenite. It seems, however, probable that in general their origin has been similar to that of the modern bog- and lake-ores. Deposits of magnetite, as a rule, do not continue of uniform thickness for any great distance like the enclosing rocks; and this is just what might be expected if we suppose them to have originally occurred as bog- or lake-ores, which accumulated in local hollows or depressions."²

The thinly laminated martitic and hematitic jasper-schists of the Huronian age, always remarkably free from both sulphur and calcium-phosphate, at once present themselves for explanation. Prof. Dana, in a criticism on other views,³ has attributed the origin of these iron-ores to "metamorphism from original marsh-made beds." More probably, in my opinion, the conditions consisted of a shore of some quartzose rock, rich in magnetite, whose débris the waves and currents strewed over the sea-bottom, alternately with thin sheets of quartz-granules and magnetite-crystals, partially concentrating the one or the other material in numerous heaps or thicker layers. In the progress of the metamorphism and contortion

¹ F. Wöhler, *Early Recollections of a Chemist*, Am. Chem., 1875, vi, 131.

² B. J. Harrington, *Geol. Surv. Canada, Rep. Prog.*, 1873-1874, 195.

³ *Am. Jour. Sci.*, 1881 (iii), xxii, 402.

to which the layers were subjected, their compact and lenticular forms were further developed, the magnetic oxide was further oxidized, partially as martite, or completely as specular ore (as already suggested by Brooks, Credner, and others), and assumed, at points where the contortion and pressure became intense, the micaceous structure and brilliant lustre of micaceous iron-ore, by a process similar to that which produces "slickensides."

The concentration of nearly pure magnetite in the deposits enclosed in the Lower Laurentian strata of Canada and the Adirondacks, and of titaniferous magnetite or menaccanite in the huge ore-beds associated with the anorthosites of the Upper Laurentian in both regions, point unmistakably to mechanical separation of feriferous sediments from different terranes: *i. e.*, in the one case from the magnetitic gneiss, in the other from the traps and anorthosites, rich in menaccanite. An examination of thin sections of diabase from dykes cutting pure magnetites in Essex County, N. Y., showed this rock to be rich in menaccanite and a possible source of such sediments.

No concentration of titanitic acid has ever been found in limonites or bog-ores. These facts seem significant of the insufficiency of any chemical theory to account for the origin of all the iron-ores.

In conclusion, it may be inferred that the mode of genesis of a bed of magnetic iron-ore may be determined with some probability by the following diagnosis.

When the ore retains structural characteristics allied to those of limonite, or encloses masses of hematite, or contains a notable amount of calcium-phosphate, a chemico-organic origin is probably indicated.

When the ore is exceptionally free from phosphorus, or is rich in titanitic or chromic acid, or is closely associated or mixed with granular garnet or olivine, a mechanical origin may be inferred